Education for Chemical Engineers 32 (2020) 40–49

Contents lists available at ScienceDirect

Education for Chemical Engineers

journal homepage: www.elsevier.com/locate/ece

Integrating environmental concerns into the teaching of mathematical optimization

María J. Fernández-Torres[a,b,*], Diane Hildebrandt[b], Baraka Celestin Sempuga[b], José A. Caballero[a]

[a] Institute of Chemical Process Engineering, University of Alicante, Apartado 99 E-03080, Spain

[b] Institute for the Development of Energy for African Sustainability (IDEAS), College of Science, Engineering and Technology, University of South Africa (UNISA), c/o Christiaan de Wet & Pioneer Avenue, Florida Campus 1710, Johannesburg, South Africa

A R T I C L E I N F O

Article history:
Received 14 January 2020
Received in revised form 17 May 2020
Accepted 19 May 2020
Available online 22 May 2020

Keywords:
Sustainable development goals (SDGs)
Cradle-to-Cradle (C2C)
Human excreta
Waste to energy
Optimal logistics
Mixed integer linear programming (MILP)

A B S T R A C T

Given the damage that the natural environment suffers from human activities, it is relevant to provide ecological literacy to all Chemical Engineering students. Sometimes, this information is offered through elective courses and/or seminars and consequently it might not reach the whole class. Some courses have more obvious connections to environmental issues, while others do not appear to. In this paper, we aim to show through some solved examples how to introduce an environmental topic in the subject Mathematical Optimization. The problems goal is to decide on the best logistics for the transport and management of human waste that will be used in the production of sustainable energy. The context is that of improving the sanitation and hygiene in areas of the developing world, while simultaneously creating job opportunities within the communities. The research that we have conducted for finding the proper way to address the environmental analysis in class, led us first to the Sustainable Development Goals (SDGs), but later on, other theories such as the Cradle-to-Cradle (C2C) have proven to be more comprehensive and therefore, better. We believe that this multidisciplinary paper shows how to integrate environmental concerns and understanding in the Chemical Engineering curricula.

1. Introduction

Studies on environmental degradation, management, pollution etc., have become a hot topic in research papers in the last decades. Evidence of this is the number of new journals that have appeared to properly present these research outcomes. Future engineers should be aware of environmental issues and concerns in order to develop critical thinking about sustainable development. According to (Bonnett, 2010), it is important to provide environmental education to avoid that students effectively become just process operators that perpetuate business as usual, causing serious environmental problems.

What we are witnessing is that in general only interested students receive some information through elective summer programs, elective courses or by voluntary attendance of seminars outside the standard contact hours. A different approach that would reach the whole class and not just the interested students would be ideal. This is the main intention of this paper. Given its characteristics, it is easier to include environmental topics in certain courses while it may seem to be less easily done in other subjects. For instance, including environmental issues in Mathematical Optimization does not seem to be obvious; but we will show that it is possible through contextualizing the tutorial problems. These problems can be given with just the essential information (barebone) to proceed straightaway to the required calculations, or they can be transformed in a way that the same mathematical problem is given with an environmental context that can motivate class discussion.

1.1. Choosing the way for the environmental topic analysis

Once the environmental topic has been chosen and added to the problem statement, there are different possibilities for its analysis. One option is to use the so-called Sustainable Development Goals (SDGs) (see Fig. 1) and work through them. In the year 2015 the leaders of all Member States of the United Nations (UN) agreed on a set of 17 Goals (SDGs) for the progress of the world to 2030 (UN, SDGs web). These Goals intend to represent who we want to be in a decade from now. According to the UN (UN, SDGs web), there is an urgent call for action by all countries, therefore, educators at all lev-

* Corresponding author.
E-mail address: fernandez@ua.es (M.J. Fernández-Torres).

https://doi.org/10.1016/j.ece.2020.05.005
1749-7728/

17 SDGs	1 No Poverty	2 Zero Hunger
3 Good Health and Well-being	4 Quality Education	5 Gender Equality
6 Clean Water and Sanitation	7 Affordable and Clean Energy	8 Decent Work and Economic Growth
9 Industry, innovation and infrstructure	10 Reduced Inequalities	11 Sustainable Cities and Communities
12 Responsible Consumption and Production	13 Climater Action	14 Life Below Water
15 Life on Land	16 Peace, Justice and Strong Institutions	17 Partnerships for the Goals

Fig. 1. Sustainable Development Goals (UN, SDGs web).

els, including universities (Sarabhai, 2016; SDSN_Australia/Pacific (2017); UNESCO, 2017), have a critical role to play in the achievement of these goals. That said, (Kopnina, 2016, 2018, 2020) show concern for the outcomes of applying just the SDGs because these assume Nature as a commodity that can be used as a resource or as an ecosystem service; therefore, analyzing environmental problems through the Goals might induce environmental and social unsustainability. According to this author, these Goals somehow justify business-as-usual by assuming that it is possible to disconnect the link between Nature resource consumption and economic growth. Because there is a biophysical limit to growth (Rees, 2020), these Goals can aggravate the environmental problems by excluding nonhuman species that will lead to more biodiversity loss, pollution, climate change and inevitably social tensions. Instead of using the SDGs, this author advocates to use circular economy and Cradle-to-Cradle (C2C) theory (Kopnina, 2019; McDonough and Braungart, 2002). C2C theory roughly means the opposite of what we are doing at present: producing goods that have a life cycle from cradle to grave. The bottom line is to produce goods bearing in mind the whole cycle of the materials involved. The concept of *waste* must disappear; according to (McDonough and Braungart, 2002) there are two types of waste: *biological waste* that can be integrated in the biological cycle and *technical waste* that should not abandon the technical cycle. The whole point is to guarantee that "waste = food", like Natural cycles do.

1.2. Preamble to the case studies

As stated above, mathematical optimization problem statements can be offered through a narrative with an environmental focus in order to raise awareness and elicit reflexive thinking and in-class discussion. The academic solved problems presented here deal with human waste management in the context of informal settlements in a developing country. This waste can cause serious health problems if not dealt with properly (Barberton et al., 2016; Taing et al., 2013). An almost universal way to "get rid" of human waste is by using flush-toilets connected to a water-flushed network of sewers. This solution is lately being under debate (Baz et al., 2008; Troy, 2008) because of the vast amount of potable water being flushed through the toilet (EPA, 2020) and the associated stress to the ecosystem.

On the other hand, another aspect to take into consideration is that human waste could be treated as a source of energy if fed to anaerobic biodigesters. These digesters are considered to be environmentally friendly devices to obtain clean energy from waste (Morgan et al., 2017). When biodegradable waste is fed to anaerobic bio-digesters, it simultaneously produces valuable biogas and organic fertilizer with multiple positive outcomes (Ding et al., 2012). Many anaerobic bio-digesters constructed all over the globe, use cattle manure as feed material. There is little reported research on bio-digesters fed with human excreta, but that which is published is positive (Andriani et al., 2015; Colón et al., 2015; Dahunsi and Uranusi, 2013; Ding et al., 2012; Mudasar and Kim, 2017; Muralidharan, 2017; Owamah et al., 2014; Sun et al., 2017). The use of human waste has become a topic of renewed interest in the context of energy generation since it is an abundant renewable source of energy that has a negative environmental impact if not treated properly (Mudasar and Kim, 2017).

Given this context, the academic problems that we present below address these environmental and social situations by suggesting the installation of new dry toilets in the households of the deprived areas under study. These dry toilets are equipped with removable cassettes that enables collection and transport of waste in a hygienic manner (Holmlund and Windh, 2018). The bottom-line behind these problems is to send the collected cassettes to centralized bio-digesters for the provision of energy to public buildings like schools or hospitals. These multidisciplinary problems are very useful for introducing environmental concern to Chemical Engineering students because they have the potential to bring interesting debates to the classroom. Some of the issues that can be tackled are: (a) the importance of human waste management, (b) the significance of using potable water for getting rid of such waste, (c) the relevance of anaerobic biodigestion dealing with biological waste and (d) the applicability of mathematical optimization in solving logistic problems, etc. The discussion can then go as far as talking about what is an "ecocentric worldview" where humans, non-humans, entire ecosystems etc., have moral value (Washington et al., 2018). This line of thinking clearly challenges the following quote from 20th century that seems to still encompass prevailing attitudes (quote-website, 2020): "*Engineering is the art of organizing and directing men and controlling the forces and materials of nature for the benefit of the human race*".

1.3. Overview to the case studies

After that preliminary presentation and discussion, the student can concentrate in the chemical engineering problem, i.e., calculating the optimized logistic for the transportation of human waste to properly manage a resource recycling-oriented society. This means that the student must develop an optimal logistics solution to collect all the human waste and carry it to the most appropriate biodigestion site at the right time with the intention to make the operation as efficient and as cheap as possible. Two problems are presented here that can be used in problem solving tutorials for the subject of optimization in the context of chemical engineering. The second problem is an extension of the first one and can be used for a subsequent tutorial session or as a final year project. The solved problems are provided first, at an easy level for the non-specialist, but it is also provided in its proper format for the experts.

2. Methodology

We propose that lecturers address the first 15–20 min of the tutorial with a general overview of the serious hygiene problem

Table 1
Transportation costs and distance between supply and demand areas for case study 1. There is a fixed amount (rental) plus a variable part depending on the number of cassettes transported ($x_{i,j,m}$). IS = Informal Settlement.

	University (j = u)[€/month]	Hospital (j = h)[€/month]
IS1 (i = 1)	$500 + 0.05x_{i,j,m}$ (42 km)	$160 + 0.1x_{i,j,m}$ (13 km)
IS2 (i = 2)	$544 + 0.01x_{i,j,m}$ (45 km)	$128 + 0.06x_{i,j,m}$ (11 km)
IS3 (i = 3)	$704 + 0.07x_{i,j,m}$ (59 km)	$384 + 0.1x_{i,j,m}$ (32 km)

Table 2
Number of cassettes that need to be removed from the settlements.

Month	# cassettes from settlement 1	# cassettes from settlement 2	# cassettes from settlement 3
Jan	5123	8122	13427
Feb	13388	16870	15869
March	15869	16870	17456
April	11388	11246	15869
May	13388	16870	17456
June	13388	16870	17456
July	8537	10122	15869
Aug	13388	16870	15456
Sept	13388	16870	15869
Oct	13388	16870	17456
Nov	13388	16870	15869
Dec	6773	17713	16113

Table 3
Costs associated to gathering the cassettes. These costs are fixed and independent on the month. IS = Informal Settlement.

	Gathering costs(€/month)
IS1	17851
IS2	22493
IS3	23274

Table 4
Maximum demand of cassettes by the two anaerobic bio-digesters considered in case study 1.

Month	# of cassettes/month Demand area University	# of cassettes/month Demand area Hospital
January	27000	41000
February	27000	41000
March	27000	41000
April	27000	41000
May	27000	41000
June	27000	45000
July	27000	45000
August	27000	45000
September	27000	45000
October	27000	45000
November	27000	45000
December	27000	45000

that informal settlements bear and the option of using dry toilets with cassettes that once full, can be sent to centralized biodigesters. After that, there can be a brief presentation on the environmental impact that this waste represents if not treated properly. Finally, the discussion can evolve to consider the importance of environmental sustainability, the SDGs and finally C2C theory. After that, students can solve the logistic problem. We provide here two solved case studies. Sections 2.1 and 2.2 show the statement of the academic problems. The mathematical modelling and solutions appear in subsequent sections.

2.1. Case study 1 – problem statement

It is desired to find an optimized logistics solution for the transportation planning to distribute the raw material (cassettes containing human waste) from three informal settlements (supply areas) to two bio-digesters (demand areas). Assume two bio-digesters already functioning, one on the premises of a university and the other at a hospital. The cost and distances for transportation appear in Table 1 from the three informal settlements to the bio-digesters sites. These costs are divided in two parts: a fixed amount due to the rental of the truck (with driver) which is independent of the number of cassettes transported, and a variable part that takes into account the number of cassettes which influences the time taken to load and unload the truck. The number of cassettes that are transported from any of the three informal settlements (i) to any of the two bio-digester sites (j) during the month m is denoted by variable $x_{i,j,m}$ in other words, $x_{i,j,m}$ is the size of shipment.

The cassettes of these new toilets are assumed to be full after 2 days in a household of 6 members. Therefore, each family requires 15 cassettes per month. The number of cassettes to be removed from each informal settlement depends on the calendar month (Table 2) given the fluctuations of inhabitants in holiday periods. These values arise by setting the number of families in each settlement: 873, 1100 and 1138 respectively. It is required three times per week that all cassettes be ready at a pickup point in each settlement to be loaded into the truck. Therefore, there must be a worker with a small van, for fetching all the cassettes from all the households to the pickup point. Table 3 shows these costs on a monthly basis. These values are independent on the month, because all the cassettes must be swapped and the worker needs to visit all the households anyway.

The planning of the transport of the cassettes is subject to: (a) The cassettes being removed three times per week (they cannot be left to accumulate in the households) and (b) the demand of cassettes by the two bio-digesters being bigger than or equal to the supply of cassettes. The latest is to guarantee that all the waste produced in the three settlements is taken to avoid sanitation problems; also to deliver the waste to the biodigesters as fresh as possible. The values of the maximum demand by the two biodigesters considered are listed in Table 4. If the energy demand from the hospital or university is not met, they need to find either, another source of bio-waste (e.g., cattle manure) or acquire energy by other conventional means (e.g., electricity). Additionally, the minimum number of cassettes that must arrive to each bio-digester every month is set to 3000 cassettes.

It is thus required to optimize the flow of cassettes from the three informal settlements to the two biodigesters in order to minimize the monthly transportation cost.

2.2. Case study 2 – problem statement

This case study is an extension of the previous one. In case study 1 it is implicitly assumed that, the infrastructure of the two bio-digesters already exist. This assumption is lifted in Case study 2 and therefore the problem is formulated differently as follows: Given a set of settlements, each one with a known monthly waste generation (cassettes), given also a set of possible locations for the bio-digesters and their associated installation and operational costs, determine which bio-digesters must be installed, as well as, the amount of cassettes that they need to be supplied each month. Case study 2 applies to the same settlements as before hence, Tables 2 and 3 are still applicable. Assuming that there are six possible bio-digesters to be built therefore, we need to substitute Tables 1 and 4 with 5 and 6 respectively. Information about the installation and operational costs of the six possible bio-digesters are listed in Table 7. The installation costs have been annualized for 10 years.

Table 5
Transportation costs for case study 2. $x_{i,j,m}$ = number of cassettes. IS = Informal Settlement. BD = bio-digester. Units [€/month].

	IS1	IS2	IS3
BD1	$500 + 0.05x_{i,j,m}$	$544 + 0.01x_{i,j,m}$	$704 + 0.07x_{i,j,m}$
BD2	$160 + 0.1x_{i,j,m}$	$128 + 0.06x_{i,j,m}$	$384 + 0.1x_{i,j,m}$
BD3	$400 + 0.04x_{i,j,m}$	$555 + 0.1x_{i,j,m}$	$350 + 0.07x_{i,j,m}$
BD4	$280 + 0.03x_{i,j,m}$	$675 + 0.01x_{i,j,m}$	$130 + 0.04x_{i,j,m}$
BD5	$200 + 0.03x_{i,j,m}$	$101 + 0.05x_{i,j,m}$	$500 + 0.1x_{i,j,m}$
BD6	$350 + 0.1x_{i,j,m}$	$500 + 0.08x_{i,j,m}$	$800 + 0.08x_{i,j,m}$

Table 6
Maximum demand of cassettes by the six anaerobic bio-digesters (BD) considered in case study 2. Units (cassettes/month).

Month	BD1	BD2	BD3	BD4	BD5	BD6
Jan	7000	41000	8000	3500	5000	45000
Feb	27000	41000	8000	25000	50000	45000
March	27000	41000	8000	25000	50000	45000
April	27000	41000	8000	25000	50000	45000
May	27000	41000	8000	25000	50000	45000
June	27000	45000	8000	25000	50000	45000
July	27000	45000	30000	3500	5000	55000
Aug	27000	45000	30000	35000	50000	55000
Sept	7000	45000	30000	35000	50000	55000
Oct	27000	45000	30000	25000	50000	55000
Nov	27000	45000	30000	25000	50000	55000
Dec	27000	45000	30000	3500	5000	55000

Table 7
Installation and operational costs of the six possible bio-digesters (BD) considered.

	Installation cost (€/year)	Operational cost (€/month/cassettes)
BD1	1700	$0.12x_{i,j,m}$
BD2	2000	$0.27x_{i,j,m}$
BD3	1500	$0.19x_{i,j,m}$
BD4	1800	$0.43x_{i,j,m}$
BD5	1400	$0.24x_{i,j,m}$
BD6	2200	$0.38x_{i,j,m}$

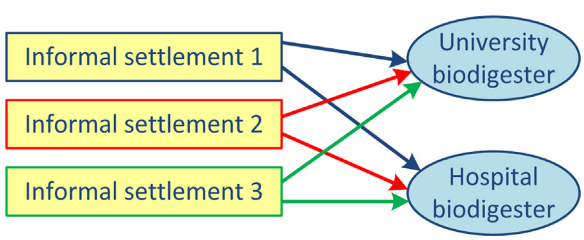

Fig. 2. Network representation of the transportation problem posed in case study 1. Distances are listed in Table 1.

2.3. Mathematical model formulation for case study 1

Mathematical optimization will be used to solve the logistic problems posed. The exact mathematical formulation could be given straight away but, given that not all Chemical Engineering academics are experts in optimization, we have decided to provide two presentations for the mathematical model: A simplified description intended for the non-specialist in mathematical optimization (this section), and the same but in its formal presentation for the expert in the subject (Appendix).

The mathematical model for the resolution of the first case study corresponds to basically with an extended multi-period transportation approach (Pochet and Wolsey, 2006), i.e., the situation is different every month. The general objective of these type of problems is to schedule the shipments from sources to destinations so that the total cost related to activities in origin, destination and transportation are minimized. Fig. 2 shows the network representation of the transportation problem we intend to solve. The three settlements are the "sources" of cassettes, and the university and hospital biodigesters are the "destinations". Each destination is linked to every source by an arrow to show all the combinations for the transport to take place. Therefore, there are 5 nodes in Fig. 2, three nodes for the sources and two for the destinations.

We need to describe the different sets that we use in the model. There are 3 sets:

i = supply node, i.e., the settlements 1, 2 and 3 = [1, 2, 3]

j = demand node, i.e., university and hospital = [u, h]

m = time period = [Jan, Feb, March, April, May, June, July, Aug, Sept, Oct, Nov, Dec]

The objective is to determine the number of cassettes that must be delivered in each time-period from all settlements to the two bio-digesters. To that end we need to define the variables in the model. For this particular case, we have used two kinds of variables: positive and binary variables. $x_{i,j,m}$ is a positive variable which defines the number of cassettes being delivered from "i" to "j" per month "m". We also need to introduce a binary variable to be employed as decision variables (yes-or-no variables). The symbol $y_{i,j,m}$ represents the binary variable for this case study. $y_{i,j,m}$ will account if the transport from "i" to "j" occurs in month "m". There are only two options: YES ($y_{i,j,m}$ =1) or NO ($y_{i,j,m}$ =0). The values of the optimized variables $x_{i,j,m}$ and $y_{i,j,m}$ will be found once the mathematical optimization has been finalized.

For the mathematical optimization to take place, we need to define a quantifiable objective function and a set of quantifiable restrictions (constraints) for the variables.

2.3.1. Objective function

In this logistic optimization case study, we need to minimize the total cost of transport. Each arrow in Fig. 2 is associated to a cost shown in Table 1, therefore, we need to consider these 6 costs (one per arrow) which change every month due to the value of $x_{i,j,m}$. We need to also add to the objective function the costs shown in Table 3. Eq. (1) summarizes in a single expression the objective function, total costs orf $\left(y_{i,j,m}, x_{i,j,m}\right)$, that depends on variables $x_{i,j,m}$ and $y_{i,j,m}$.

$$f\left(y_{i,j,m}, x_{i,j,m}\right) = \sum_{m} \left[\begin{array}{l} (500y_{1um} + 0.05x_{1um}) + (544y_{2um} + 0.01x_{2um}) + (704y_{3um} + 0.07x_{3um}) + \\ + (160y_{1hm} + 0.1x_{1hm}) + (128y_{2hm} + 0.06x_{2hm}) + (384y_{3hm} + 0.1x_{3hm})] \end{array} \right] + (17851 + 22493 + 23274) \times 12 \tag{1}$$

The reason to sum over all "m" is that the number of cassettes shipped each month and the options to ship or not to ship, change on a monthly basis. Notice that the fixed costs shown in Table 1 are now multiplied by the binary variable $y_{i,j,m}$ in Eq. (1). The inclusion of this binary is necessary because if the transport does not take place, the fixed cost amount should not be taken into account in the cost equation. If we refer, in general, to the fixed costs as $Cf_{i,j,m}$, to the variable costs as $Cv_{i,j,m}$ and to the gathering costs as G_i, then, Eq. (1) can be formally rewritten as:

$$f\left(y_{i,j,m}, x_{i,j,m}\right) = \sum_{m}\sum_{i}\sum_{j}\left(Cf_{i,j,m}y_{i,j,m} + Cv_{i,j,m}x_{i,j,m}\right) + \sum_{i} G_i \times 12 \tag{2}$$

2.3.2. Constraints of the model

The constraints are conditions written as mathematical expressions that force the supply and demand to be satisfied. In a transportation problem, there is at least one constraint for each node. All the constraints that need to be included in the model will be explained below.

Let's start by the supply-node constraints. In this case, all the cassettes need to be taken away, i.e., all the cassettes at each source-node must be removed. Mathematically, this constraint is shown in Eq. (3) for all (∀) combinations of "m" and "i".

$$\sum_j x_{i,j,m} = Supply_{m,i} \qquad \forall m, i \tag{3}$$

Eq. (3) represents a collection of 36 equations by using all the combinations of "i" and "m". This equation states that the sum of all the cassettes leaving from informal settlement "i" in one particular month to arrive to any of the two biodigesters ("j"), must equal the supplied amount (Table 2). It might be helpful to see in detail the first 3 equations from Eq. (3) for the particular month of January.

$$\left.\begin{aligned} x_{1,u,Jan} + x_{1,h,Jan} &= 5123 \\ x_{2,u,Jan} + x_{2,h,Jan} &= 8122 \\ x_{3,u,Jan} + x_{3,h,Jan} &= 13427 \end{aligned}\right\} \tag{4}$$

The equal sign in Eq. (3) and (4) implies that the supply of cassettes must be removed to either the university or the hospital but, for sanitary reasons, it cannot be left to accumulate in the informal settlement.

Let's move on now to the demand-node constraints. The biodigester cannot work over its design capacity (upper bound), and at the same time, there is a minimum number of cassettes (lower bound) that need to be transported to the different bio-digesters so that the biodigestion does not get upset. Mathematically, the upper bound constraint for the demand (Table 4) can be written as follows:

$$\sum_i x_{i,j,m} \le Demand_{m,j} \qquad \forall m, j \tag{5}$$

Eq. (5) represents a collection of 24 equations which state that the sum of all the cassettes arriving to "j" in one particular month "m" from any of the three informal settlements "i", must be equal or smaller than the maximum demanded amount (Table 4), i.e., the digester should not be fed with more input material than that required by design. It might be helpful to see in detail the first 2 equations from Eq. (5) for the particular month of January.

$$\left.\begin{aligned} x_{1,u,Jan} + x_{2,u,Jan} + x_{3,u,Jan} &\le 27000 \\ x_{1,h,Jan} + x_{2,h,Jan} + x_{3,h,Jan} &\le 41000 \end{aligned}\right\} \tag{6}$$

On the other hand, the lower bound constraint for the demand is described mathematically by Eq. (7). The same, but easier version of this, are the 2 equations shown in Eq. (8). There are only 2 equations because the minimum number of cassettes that must arrive to each bio-digester is the same every month.

$$\sum_i x_{i,j,m} \ge 3000 \qquad \forall j, m \tag{7}$$

$$\left.\begin{aligned} x_{1,u,m} + x_{2,u,m} + x_{3,u,m} &\ge 3000 \\ x_{1,h,m} + x_{2,h,m} + x_{3,h,m} &\ge 3000 \end{aligned}\right\} \tag{8}$$

We still need to add more constraints for the model to be complete. The model also needs to somehow link variable $x_{i,j,m}$ to the value of $y_{i,j,m}$, i.e., it must make 0 variable $x_{i,j,m}$ if variable $y_{i,j,m}$ is set to 0, and leave it to vary freely if $y_{i,j,m}$ acquires the value 1. This condition which looks like common sense and pointless to be written, is actually necessary for the model to function properly, otherwise we might obtain the unreasonable result that $x_{i,j,m}$ is different to

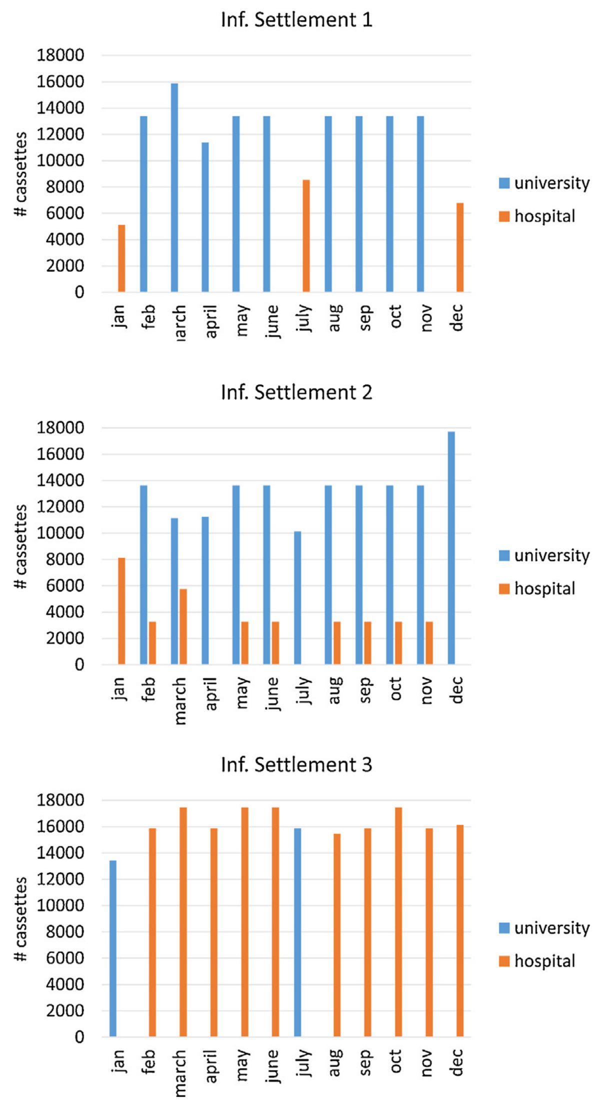

Fig. 3. Detail of the optimal numbers of cassettes transported per month from the different settlements to the university and hospital (case study 1).

0, meanwhile $y_{i,j,m}$ is 0 for the same "i, j, m" combination. Mathematically this is written as in Eq. (9) where the so called "big M" (a big number) is used.

$$x_{i,j,m} \le My_{i,j,m} \qquad \forall i, j, m \tag{9}$$

This equation satisfies the above requirements because if $y_{i,j,m}$ is zero, then $x_{i,j,m}$ will automatically become zero. On the contrary, if $y_{i,j,m}$ is 1, then $x_{i,j,m}$ can be any positive value smaller than M. The value of M is chosen to be the highest number in Table 2 because $x_{i,j,m}$ will never surpass that value.

Finally, we need an extra constraint that forces the model not to choose the trivial and useless answer that the lowest cost will be achieved if we transport *NOTHING*, i.e., we need to force the model not to choose all $x_{i,j,m}$ equal zero, given that it is required to transport the cassettes. This constraint for the model is stated in Eq. (10).

$$\sum_j y_{i,j,m} \ge 1 \qquad \forall i, m \tag{10}$$

Eq. (10) represents 36 equations. For the month of January, this expression is shown in Eq. (11) with the following interpretation: The cassettes from each settlement must be transported to either the university or the hospital, i.e., at least one of the two decision

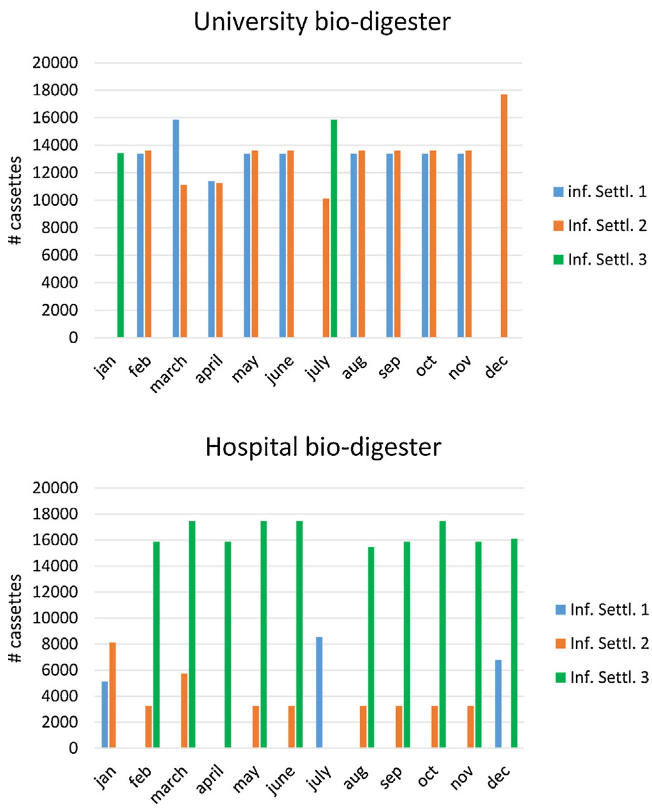

Fig. 4. Detail of the optimal number of cassettes that must be transported per month to the university and hospital from the three settlements under consideration (case study 1).

variables, $y_{i,u,m}$ or $y_{i,h,m}$, must be equal to one (although, it is also possible that both turn out to be simultaneously equal to one).

$$\left.\begin{array}{l} y_{1,u,Jan} + y_{1,h,Jan} \geq 1 \\ y_{2,u,Jan} + y_{2,h,Jan} \geq 1 \\ y_{3,u,Jan} + y_{3,h,Jan} \geq 1 \end{array}\right\} \tag{11}$$

The model described contains binary and continuous variables. All the equations are linear, therefore we have ended up with a so called "Mixed Integer Linear Programming" problem (MILP) in the context of mathematical optimization (Pochet and Wolsey, 2006). There are many tools at our disposal to solve linear programming problems, but the preferred tool is GAMS (General Algebraic Modeling System) since it is specifically designed for mathematical optimization. GAMS consists of a language compiler and a set of high-performance solvers for complex, large scale modelling applications. This is the reason why Eqs. 2,5 and 7 and 10 have been presented in a more contracted manner, so that the GAMS user can write many (sometimes thousands) equations in a single command. The Supplementary Material provided contains the exact file of GAMS that we have used.

2.4. Mathematical model formulation for case study 2

This paper also contains the formal version for case study 2 in the Appendix. We have now to consider the possibility to send the cassettes to six bio-digesters (BD) that have not being constructed yet. The optimization will indicate which bio-digester(s) should be built and operated. The set "j" now changes to six elements:

j = demand node = [BD1, BD2, BD3, BD4, BD5, BD6]

Fig. 5. Detail of the optimal numbers of cassettes transported per month from the different settlements to the bio-digesters that will be built (case study 2).

We can use some of the equations already presented in Section 2.3 for case study 1 but, we also need to add new variables, constraints and reformulate the objective function.

We need two new positive variables to describe the added extra cost for the installation (CI_j) and operation (CO_j) of each bio-digester (Table 7). In addition, we need another binary variable (w_j) to account if the bio-digester is going to be built (w_j =1) or not (w_j =0). The new objective function is based on Eq. (2), but we need to add the installation costs (CI_j) multiplied by the binary variable w_j, plus the operational costs (CO_j) multiplied by $x_{i,j,m}$.

$$f\left(y_{i,j,m}, x_{i,j,m}, \ w_j\right) = \sum_m \sum_i \sum_j \left(Cf_{i,j,m} y_{i,j,m} + Cv_{i,j,m} x_{i,j,m}\right) + \sum_i G_i \times 12 + \sum_j \left(CI_j w_j + \sum_i \sum_m CO_j x_{i,j,m}\right) \tag{12}$$

The reasoning behind Eq. (12) is very similar to the explanation already given for Eq. (1). For this case study we need to also add an extra constraint that establishes that if a bio-digester should not be built then, there must be no transport between any settlement to that bio-digester. This constraint is shown in Eq. (13) and it can be

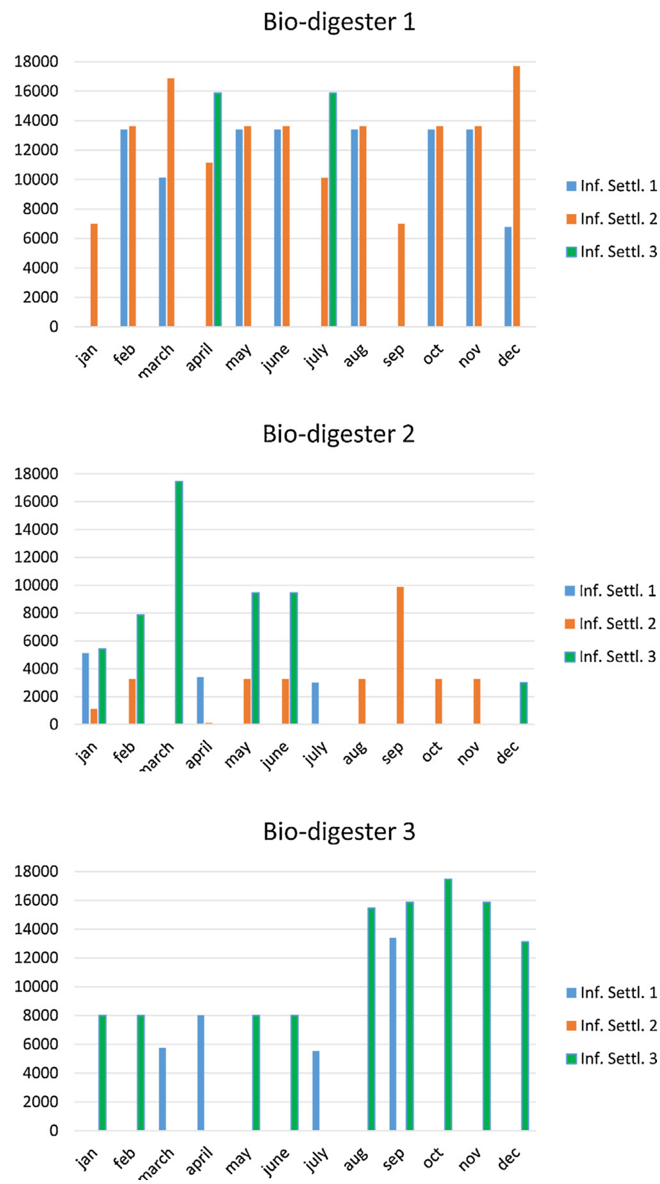

Fig. 6. Detail of the optimal number of cassettes that must be transported per month to the bio-digesters that will be built from the three settlements under consideration (case study 2).

explained as follows: if $w_j = 0$ (the bio-digester will not be built) then, any $y_{i,j,m}$ is forced to become zero as well. The approach to reach to such statement appears in the Appendix for the formal description.

$$w_j + \sum_i \sum_m \left(1 - y_{i,j,m}\right) \geq 1 \quad \forall j \tag{13}$$

This second model contains again linear equations, binary and continuous variables, therefore, we have ended up with another (MILP) problem. The Supplementary Material provided contains the exact file of GAMS that we have used.

3. Results of the case studies

After writing the data and equations in GAMS as shown in the Supplementary Material, the application solves all the equations simultaneously and provides the results. For case study 1 these results contain the 72 different values of $y_{i,j,m}$ and the corresponding 72 for $x_{i,j,m}$. There are 72 because the application finds out all the different options of 3 settlements × 2 bio-digesters × 12 months = 72. These values have been presented in Fig. 3 (from the point of view of the supply) and Fig. 4 (from the point of view of the demand). Fig. 3 shows that for most of the months the cassettes from informal settlement 1 must be sent to the university, except for January, July and December where the cassettes should be sent to the hospital. As for informal settlement 2, there is a distribution of cassettes between the two bio-digesters that is difficult to predict beforehand. For most of the year, Informal settlement 3 must send its cassettes to the hospital, but during January and July the cassettes must be sent to the university. From Figs. 3 and 4 it can be deduced that the answer to the problem is not trivial for a quite small size problem like this. The optimized cost of the project for case study 1 is €811064/year.

Turning our attention now to the results corresponding to case study 2, we obtained that only three out of the six possible bio-digesters need to be constructed. The values of the binary variable accounting for this, w_j, are $w_{BD1} = 1, w_{BD2} = 1, w_{BD3} = 1, w_{BD4} = 0$, $w_{BD5} = 0$ and $w_{BD6} = 0$. Figs. 5 and 6 show the distribution for transporting the cassettes for case study 2. As in case study 1,

Table 8
List of positive contributions from the project to some of the Sustainable Development Goals (SDGs).

Goal	Positive contribution
1	Poverty can be alleviated because the project, if implemented, could contribute to job creation
3	The installation of new dry toilets can help prevention of diseases
6	Better sanitation and hygiene if the project works well and the cassettes are removed on time and swapped by empty ones
7	The project aims to also produce bio-gas which is a type of sustainable energy
8	The project has the potential to promote safe and secure new jobs derived
9	The new dry toilets somehow means infrastructure development
12	The project implies the consumption of sustainable energy for the university and hospital. The recycling of human waste contributes positively to this goal
13	The biogas consumed by the university and hospital will not contribute to climate change
15	The fertilizer produced from the biodigestion could be used to restore forest land

Table 9
C2C discussion outcomes of the project.

Sustainable part of the project	Dubious sustainable part of the project
A waste material (human waste) can be used as food to produce sustainable energy and ecological fertilizer.	The entire portable toilets, cassettes and biodigester should be constructed of a material that after their lifespan either degrades becoming biological waste or that it can be used in a technological cycle. All the vehicles used in the project should consume green energy.

Figs. 5 and 6 show that the optimal answer to the problem is not trivial and impossible to be solved manually. The optimized cost of the project for case study 2 is €809,883/year for transport considerations only (similar to the amount obtained in case study 1). We need now to add the cost of installation and operation of the three bio-digesters selected. The latest amount is €91,522/year. Therefore, the total amount is €901,405/year.

4. Discussion of the environmental topic

The solved case studies presented above offer the student the opportunity to evaluate which parts of the project positively contribute to the SDGs. Most likely students will point out to Goals number 1, 3, 6, 7, 8, 9, 12, 13 and 15 (see Fig. 1). Table 8 shows in brief possible answers. A reasonable question that must be derived from the Goals analysis is the following: is this project entirely sustainable? An analysis by means of the C2C theory clearly indicates that even though the central part of the project is environmentally sustainable (produce sustainable energy and ecological fertilizer from human waste) there are other parts that might not be. A list of discussion outcomes from the C2C theory appears in Table 9. The discussion in class about the project could be extended further through the following considerations: Can poverty reduction be decoupled from economic growth that entails consumption of natural resources? If a different economic system is not going to be implemented, how can we guarantee that by raising the standard of living of poor communities it is still possible to avoid potential catastrophic impacts on the global ecosystem? If the ecosphere is going to be damaged as a result of economic growth, how can intergenerational and interspecies justice be addressed in a democratic system? Perhaps a bit of economic deliberation is also appropriate at this stage. According to Rees (2020) the neoliberal thinking assumes that the economy and the ecosphere are two independent systems, but this author believes that they are not and that by promoting economic growth, the biophysical systems upon which our existence depends, shrinks. The biophysical laws of the biosphere clash with the economic theory that we, humans, have invented. Since the laws of Nature are not going to change, (they are intrinsic to the Planet), it seems reasonable that it is us who need to adjust to Nature's cycles by adopting a new economic thinking. Some people might say that it is not possible to stop the inertia of what we have been doing for the last 200 years, but as we write this section, the COVID-19 pandemic is hitting the so-called developed countries hard, and consequently, economic activity has been voluntarily stopped by confining most citizens to their homes. The global paralysis of the economy that we are seeing is unprecedented and most governments are studying how to maneuver in the new situation. In the end, it becomes obvious that it is possible to stop the economy and change things.

5. Conclusions

A convenient and useful way to introduce environmental concern through the SDGs and the C2C theory for the Chemical Engineering curricula in the context of mathematical optimization has been illustrated. We believe that being exposed to the SDGs and its criticism is important because these Goals are at the heart of the 2030 Agenda for Sustainable Development endorsed by the United Nations. We have also presented sufficient material to further enrich the discussion with interesting topics such as "the ecocentric worldview" or "the adequacy of the economic system" which possibly can bring new perspectives to a Chemical Engineering class.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the financial support by the Ministry of Economy, Industry and Competitiveness from Spain, under the project CTQ2016-77968-C3-2-P (AEI/FEDER, UE). The authors also thank the visiting researcher program, at the University of South Africa, for financial support. We also would like to acknowledge the National Research Foundation, Mundati™ and the Institute for Social and Health Sciences for their help.

Appendix A.

In this section we provide formal presentation of the mathematical models described in the manuscript in Sections 2.3 and 2.4.

Model for case study 1

Index sets:

SETT	[i | i is a supply node] (i.e. Informal settlements 1, 2, 3)
DEM	[j | j is a demand node] (i.e. University, Hospital area)
TIME	[m | m is a time period] (i.e. calendar months)

Data

$Demand^{Lo}_{j,m}$	Minimum demand of cassettes by each bio-digester (j) in each time period (m). The value is 3000 cassettes independently of the month or biodigester.
$Demand^{up}_{j,m}$	Maximum capacity of the bio-digester j in time period m. See Table 4.
$Supply_{i,m}$	Supply of cassettes from the different settlements. See Table 2.
$Cf_{i,j}$	Fixed cost for transporting material from settlement i to bio-digester j. (€/month) See Table 1.
$Cv_{i,j}$	Variable cost for transporting cassettes from settlement i to bio-digester j. (€/month/cassette) See Table 1.

Variables

$x_{i,j,m}$	Positive variable. It is the number of cassettes transported from settlement i to bio-digester j in time period m
$Y_{i,j,m}$	Boolean variable that takes the value True if there is a delivery from settlement i to bio-digester j in time period m, and False otherwise
$Cost_{i,j,m}$	Transport cost between nodes i and j in time period m
Total Cost	Total cost

The model can be written in its disjunctive form as follows:

$$\min: \ Total\ Cost = \sum_{i \in SETT} \sum_{j \in DEM} \sum_{m \in TIME} Cost_{i,j,m}$$

$$s.t. \quad \begin{bmatrix} Y_{i,j,m} \\ Cost_{i,j,m} = Cf_{i,j} + Cv_{i,j} x_{i,j,m} \end{bmatrix} \underline{\vee} \begin{bmatrix} \neg Y_{i,j,m} \\ Cost_{i,j,m} = 0 \\ x_{i,j,m} = 0 \end{bmatrix} \quad \forall i \in SETT,\ j \in DEM,\ m \in TIME$$

$$\sum_j x_{i,j,m} = Supply_{i,m} \quad \forall i \in SETT, \forall m \in TIME$$

$$\sum_i x_{ijm} \le Demand^{up}_{j,m} \ \forall j \in DEM,\ \forall m \in TIME$$

$$\sum_i x_{ijm} \ge Demand^{lo}_{j,m} \ \forall j \in DEM,\ \forall m \in TIME$$

$$\underset{j \in DEM}{\vee} Y_{i,j,m} \ \forall m \in TIME;\ \forall i \in SETT$$

This model can be easily reformulated as a Mixed Integer Linear Programming Problem (MILP) using a hull reformulation (Ruiz, 2012). Binary variable $y_{i,j,m}$ is related to the Boolean variable $Y_{i,j,m}$. The logical relationships can be transformed in algebraic equations in terms of binary variables (Raman and Grossmann, 1991).The final model is as follows:

$$\min: \ Total\ Cost = \sum_{i \in SETT} \sum_{j \in DEM} \sum_{m \in TIME} Cost_{i,j,m}$$

$$s.t. \quad Cost_{i,j,m} = Cf_{i,j} y_{i,j,m} + Cv_{i,j} x_{i,j,m} \ \forall i \in SETT,\ j \in DEM,\ m \in TIME$$

$$x_{i,j,m} \le U_{i,m} y_{i,j,m} \ \forall i \in SETT,\ j \in DEM,\ k \in TIME$$

$$\sum_i x_{i,j,m} \ge Demand^{lo}_{j,m} \ \forall j \in DEM, \forall m \in TIME$$

$$\sum_i x_{i,j,m} \le Demand^{up}_{j,m} \ \forall j \in DEM, \forall m \in TIME$$

$$\sum_j x_{i,j,m} = Supply_{i,m} \quad \forall i \in SETT, \forall m \in TIME$$

$$\sum_j y_{i,j,m} \ge 1 \ \forall m \in TIME;\ \forall i \in SETT$$

$$x_{i,j,m} \ge 0 \ \forall i \in SETT,\ j \in DEM,\ k \in TIME$$

In the above model the parameter $U_{i,m}$ is an upper bound to the maximum amount of cassettes that can be delivered from any settlement "i" in any time period "m". The tightest value can be obtained by equating it to the supply in each settlement.

$$U_{i,m} = Supply_{i,m}$$

Model for case study 2

This model is a variation of the previous one. In this case, we have six possible bio-digesters, therefore the set "j" changes from two to six:

DEM[j | j is a demand area] (i.e. BD1, BD2, BD3, BD4, BD5, BD6)

New variables: A new Boolean variable to decide if the biodigester will be built or not, and a positive variable to calculate the incurred cost in case that the bio-digester is built.

W_j	True if the bio-digester in location "j" is built, and False otherwise.
$Cost^{BD}_j$	Cost of bio-digester in location "j" ($/year)

The new data are the installation and operation cost of each one of the potential candidates.

CI_j	Installation cost of the bio-digester in location "j" ($/year)
CO_j	Operational cost of the bio-digester ($/month/cassette)

The disjunctive model can now be written as follows:

$$\min: \ Total\ Cost = \sum_{i \in SETT} \sum_{j \in DEM} \sum_{m \in TIME} Cost_{i,j,m} + \sum_{j \in DEM} Cost^{BD}_j$$

$$s.t. \quad \begin{bmatrix} Y_{i,j,m} \\ Cost_{i,j,m} = Cf_{i,j} + Cv_{i,j} x_{i,j,m} \end{bmatrix} \underline{\vee} \begin{bmatrix} \neg Y_{i,j,m} \\ Cost_{i,j,m} = 0 \\ x_{i,j,m} = 0 \end{bmatrix} \quad \forall i \in SETT,\ j \in DEM,\ k \in TIME$$

$$\begin{bmatrix} W_j \\ Cost^{BD}_j = CI_j + \sum_{i \in SETT} \sum_{m \in TIME} CO_j x_{i,j,m} \\ Demand^{lo}_{j,m} \le \sum_i x_{i,j,m} \le Demand^{up}_j \ \forall m \in TIME \end{bmatrix} \underline{\vee} \begin{bmatrix} \neg W_j \\ Cost^{BD}_j = 0 \\ \sum_i \sum_m x_{i,j,m} \le 0 \end{bmatrix} \quad \forall j \in DEM$$

$$\sum_j x_{i,j,m} = Supply_{i,m} \quad \forall i \in SETT, \forall m \in TIME$$

$$\underset{j \in DEM}{\vee} Y_{i,j,m} \ \forall m \in TIME;\ \forall i \in SETT$$

$$\neg W_j \Rightarrow \neg \left(\underset{i \in SETT, m \in TIME}{\wedge} Y_{i,j,m} \right)$$

$$x_{i,j,m} \ge 0 \ \forall i \in SETT,\ j \in DEM,\ k \in TIME$$

Note that for this model, the lower and upper bounds on the bio-digester demand can only be met if the bio-digester is built, so it is necessary to include the demand constraints inside the disjunction where the construction of the bio-digester is considered.

We have also added a new logical relationship that states that, if a bio-digester is not built then, there is no transport between from any settlement to that bio-digester.

Again, the disjunctive model can be transformed in a MILP model using a hull reformulation. The MILP model is as follows:

$$\min: \ Total\ Cost = \sum_{i \in SETT} \sum_{j \in DEM} \sum_{m \in TIME} Cost_{i,j,m} + \sum_{j \in DEM} Cost_j^{BD}$$

$$s.t. \quad Cost_{i,j,m} = Cf_{i,j} y_{i,j,m} + Cv_{i,j} x_{i,j,m} \ \forall i \in SETT,\ j \in DEM,\ m \in TIME$$

$$Cost_j^{BD} = CI_j w_j + \sum_{i \in SETT} \sum_{m \in TIME} CO_j x_{i,j,m}$$

$$x_{i,j,m} \le U_{i,m} y_{i,j,m} \ \ \forall i \in SETT,\ \ j \in DEM,\ k \in TIME$$

$$\sum_i x_{i,j,m} \ge Demand_{j,m}^{lo} w_j \ \forall j \in DEM, \forall m \in TIME$$

$$\sum_i x_{i,j,m} \le Demand_{j,m}^{up} w_j \ \forall j \in DEM, \forall m \in TIME$$

$$\sum_j x_{i,j,m} = Supply_{i,m} \quad \forall i \in SETT, \forall m \in TIME$$

$$\sum_j y_{i,j,m} \ge 1 \ \ \forall m \in TIME;\ \forall i \in SETT$$

$$w_j + \sum_{i \in SETT} \sum_{m \in TIME} \left(1 - y_{i,j,m}\right) \ge 1 \ \ \forall j \in DEM$$

$$x_{i,j,m} \ge 0 \ \ \forall i \in SETT,\ \ j \in DEM,\ k \in TIME$$

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ece.2020.05.005.

References

Andriani, D., Wresta, A., Saepudin, A., Prawara, B., 2015. A review of recycling of human excreta to energy through biogas generation: indonesia case. Energy Procedia 68, 219–225.

Barberton, C., Townsend, M., Carter, J., 2016. Estimating the Cost of Sanitation Infrastructure for Selected Sites in Khayelitsha in City of Cape Town, in: Research, C.E. (Ed.). https://www.cornerstonesa.net/reports/2016%20Khayelitsha%20Sanitation%20Costing%20Report.pdf.

Baz, I.A., Otterpohl, R., Wendland, C. (Eds.), 2008. Efficient Management of Wastewater. Its Treatment and Reuse in Water-Scarce Countries. Springer-Verlag, Berlin, Heidelberg.

Bonnett, M., 2010. Environmental education. In: Peterson, P., Baker, E., McGaw, B. (Eds.), International Encyclopedia of Education (Third Edition). Elsevier, Oxford, pp. 146–151.

Colón, J., Forbis-Stokes, A.A., Deshusses, M.A., 2015. Anaerobic digestion of undiluted simulant human excreta for sanitation and energy recovery in less-developed countries. Energy Sustain. Dev. 29, 57–64.

Dahunsi, S.O., Uranusi, U.S., 2013. Co-digestion of food waste and human excreta for biogas production. Br. Biotechnol. J. 3, 485–499.

Ding, W., Niu, H., Chen, J., Du, J., Wu, Y., 2012. Influence of household biogas digester use on household energy consumption in a semi-arid rural region of northwest China. Appl. Energy 97, 16–23.

EPA, 2020. How Much Water Do We Use? (consulted April https://www.epa.gov/sites/production/files/2017-03/documents/ws-facthseet-indoor-water-use-in-the-us.pdf.

Holmlund, K., Windh, J., 2018. Sanitation and Waste to Value for Informal Settlements. A Field Study in Johannesburg, South Africa. http://www.diva-portal.org/smash/get/diva2:1219674/FULLTEXT02.pdf.

Kopnina, H., 2016. The victims of unsustainability: a challenge to sustainable development goals. Int. J. Sustain. Dev. World Ecol. 23, 113–121.

Kopnina, H., 2018. Teaching sustainable development goals in the Netherlands: a critical approach. Environ. Educ. Res. 24, 1268–1283.

Kopnina, H., 2019. Green-washing or best case practices? Using circular economy and Cradle to Cradle case studies in business education. J. Clean. Prod. 219, 613–621.

Kopnina, H., 2020. Education for the future? Critical evaluation of education for sustainable development goals. J. Environ. Educ., 1–12.

McDonough, W., Braungart, M., 2002. Cradle to cradle: remaking the way we make things. North Point Press, New York.

Morgan, H.M., Xie, W., Liang, J., Mao, H., Lei, H., Ruan, R., Bu, Q., 2017. A techno-economic evaluation of anaerobic biogas producing systems in developing countries. Bioresour. Technol. 250, 910–921.

Mudasar, R., Kim, M.-H., 2017. Experimental study of power generation utilizing human excreta. Energy Convers. Manage. 147, 86–99.

Muralidharan, A., 2017. Feasibility, health and economic impact of generating biogas from human excreta for the state of Tamil Nadu, India. Renew. Sustain. Energy Rev. 69, 59–64.

Owamah, H.I., Dahunsi, S.O., Oranusi, U.S., Alfa, M.I., 2014. Fertilizer and sanitary quality of digestate biofertilizer from the co-digestion of food waste and human excreta. Waste Manag. 34, 747–752.

Pochet, Y., Wolsey, L.A., 2006. Production Planning by Mixed Integer Programming (Springer Series in Operations Research and Financial Engineering). Springer-Verlag New York, Inc.

quote-website: https://www.quotes.net/quote/21396 (checked on April 2020).

Raman, R., Grossmann, I.E., 1991. Relation between MILP modelling and logical inference for chemical process synthesis. Comput. Chem. Eng. 15, 73–84.

Rees, W.E., 2020. Ecological economics for humanity's plague phase. Ecol. Econ. 169, 106519.

Ruiz, J.P., Jagla, J.H., Grossmann, I.E., Meeraus, A., Vecchietti, A., 2012. In: Kallrath, J. (Ed.), Generalized Disjunctive Programming: Solution Strategies Algebraic Modeling Systems, Vol. 104. Springer, Berlin Heidelberg, pp. 57–75.

Sarabhai, K.V., 2016. Editorial. J. Educ. Sustain. Dev. 10, 205–207.

SDSN_Australia/Pacific, 2017. Getting started with the SDGs in universities: a guide for universities, higher education institutions, and the academic sector. In: Sustainable Development Solutions Network – Australia/Pacific, Melbourne (accessed April 2020) http://ap-unsdsn.org/wpcontent/uploads/University-SDG-Guide_web.pdf.

Sun, Z.-Y., Liu, K., Tan, L., Tang, Y.-Q., Kida, K., 2017. Development of an efficient anaerobic co-digestion process for garbage, excreta, and septic tank sludge to create a resource recycling-oriented society. Waste Manag. 61, 188–194.

Taing, L., Armitage, N., Ashipala, N., Spiegel, A., 2013. TIPS For Sewering Informal Settlements. Technology, Institutions, People and Services, WRC, Report No. TT 557/13.

Troy, P. (Ed.), 2008. Troubled Waters. Confronting the Water Crisis in Australia'S Cities. Australian National University (ANU).

UN, SDGs web. https://sustainabledevelopment.un.org/post2015/transformingourworld (consulted on April 2020).

UNESCO, 2017. Education for Sustainable Development Goals (consulted on April 2020). https://www.sdg4education2030.org/education-sustainable-development-goals-learning-objectives-unesco-2017.

Washington, H., Chapron, G., Kopnina, H., Curry, P., Gray, J., Piccolo, J.J., 2018. Foregrounding ecojustice in conservation. Biol. Conserv. 228, 367–374.